Engine Icing
Modeling, Detection, and Mitigation

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September 16-17, 2015

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Outline

- Problem of Engine Icing Power Loss
- Propulsion System Lab (PSL) Engine Testing
- Modeling Engine Icing Effects
- Detection of Engine Icing Accretion
- Potential Mitigation Strategies
- Conclusions
- Future Work

Problem of Icing Induced Power Loss

- More than 150 power loss events reported in last 20 years in High Ice Water Content conditions
  - Temporary or sustained power loss, uncontrollability, engine shutdown
- Many possible causes of power loss:
  - Compressor surge
  - Flame-out due to combustor ice ingestion
  - Damage due to ice shedding
  - Sensor icing
  - Engine rollback
- Ice crystals are believed to enter the core, melt, and accrete on engine components
- No pilot reports of weather radar returns
- No observations of airframe icing

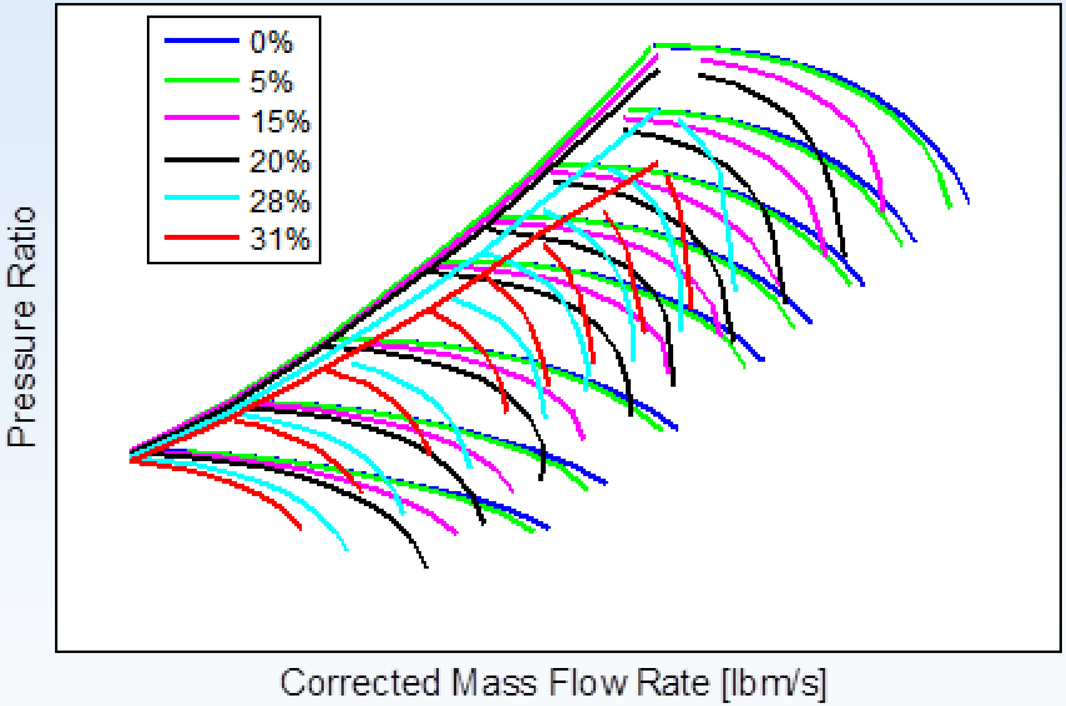
PSL Engine Icing Testing

- In order to gain more insight into turbofan engine icing, a dual spool turbofan engine was tested in 2013 at the Propulsion System Lab (PSL) at NASA Glenn Research Center
- The engine used was known to be prone to engine icing
- Testing conditions:
  - Baseline steady states at various operating conditions established
  - Ice crystal cloud injected into the engine airstream
    - Accretion of ice in the LPC observed
    - In some case resulted in loss of engine power (rollback)

Modeling of Engine Ice Accretion

LPC Performance Effect

- LPC maps with various quantities of ice blockages in the first few rows of stators was developed by Icing Branch
- Linear interpolation between maps during the progress of the ice accretion
- NPSS simulation of the ice accretion was first developed
- T-MATS version of the engine model was also developed to study the controller interaction with ice accretion

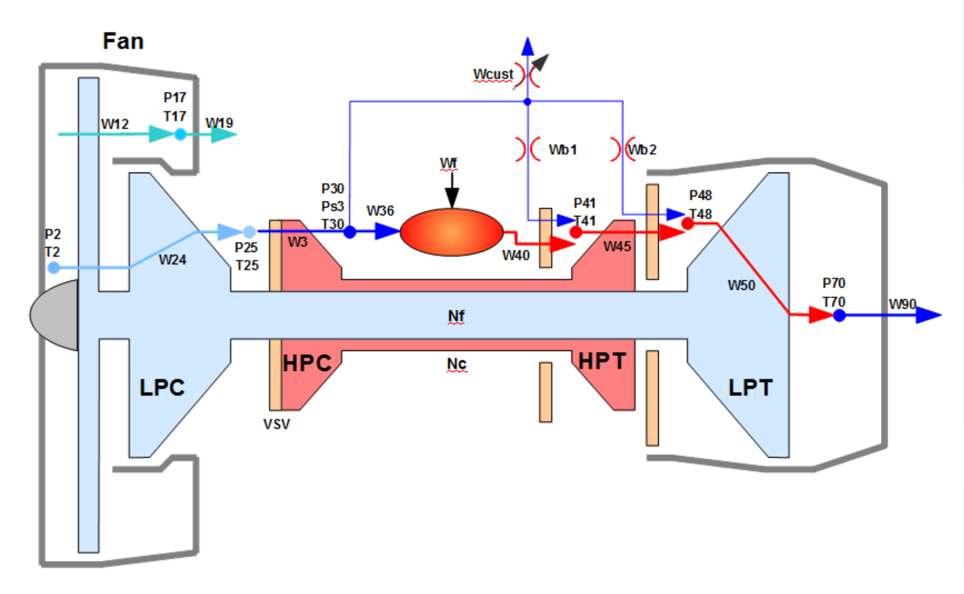


Ref: Jorgenson, P., Veres, J, Jones, S, "Modeling the Deterioration of Engine and Low Pressure Compressor Performance During a Roll Back Event due to Ice Accretion," AIAA Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.

T-MATS Models

Engine Geometry:

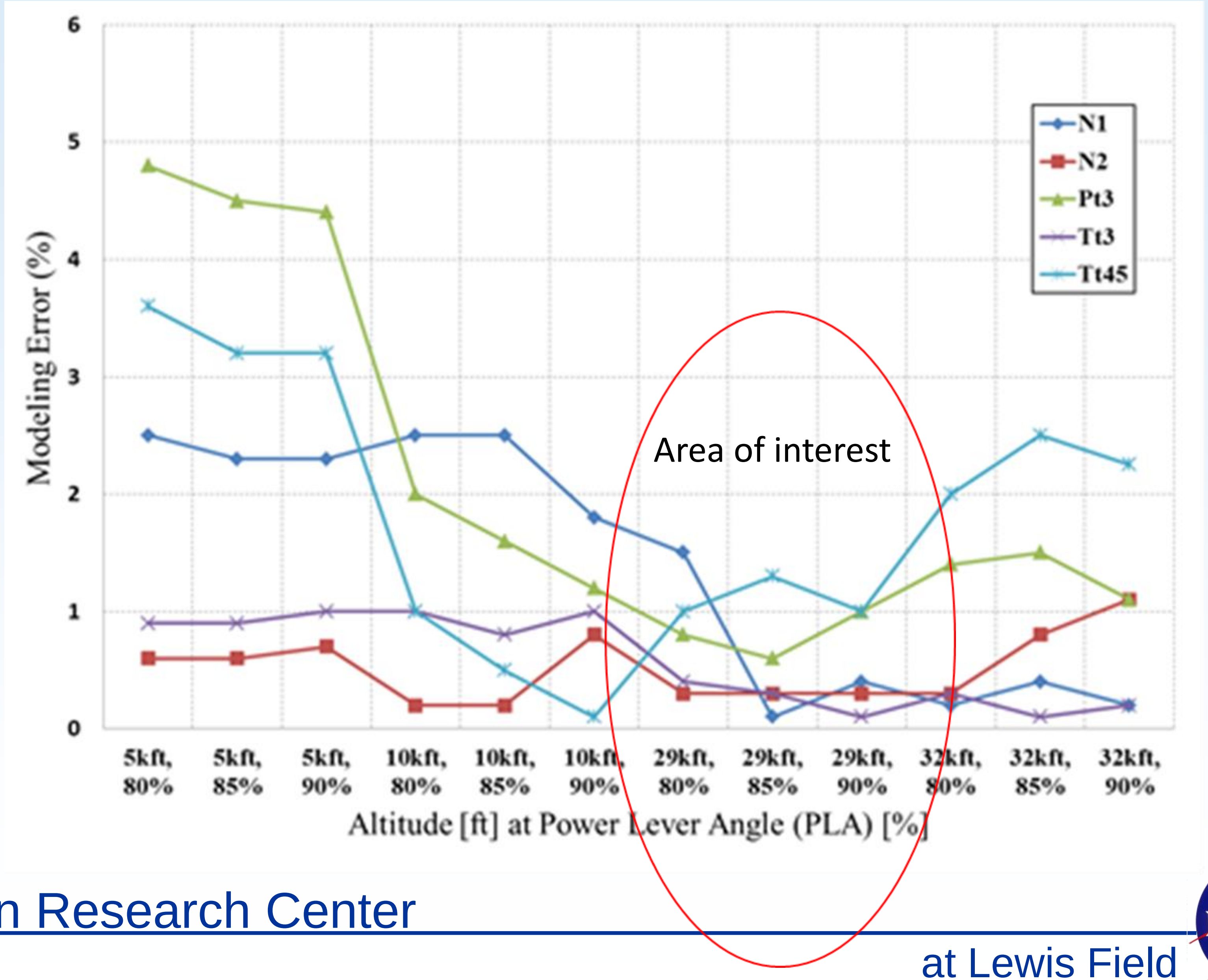
- 2 Spool
- High Bypass
- HPC bleed cooling flow to HPT and LPT



Modeling Effort:

- Baseline engine model matched to steady state performance data
- Icing engine model assuming ice build up affects LPC performance map
- Heat transfer due to ice ingestion is also simulated

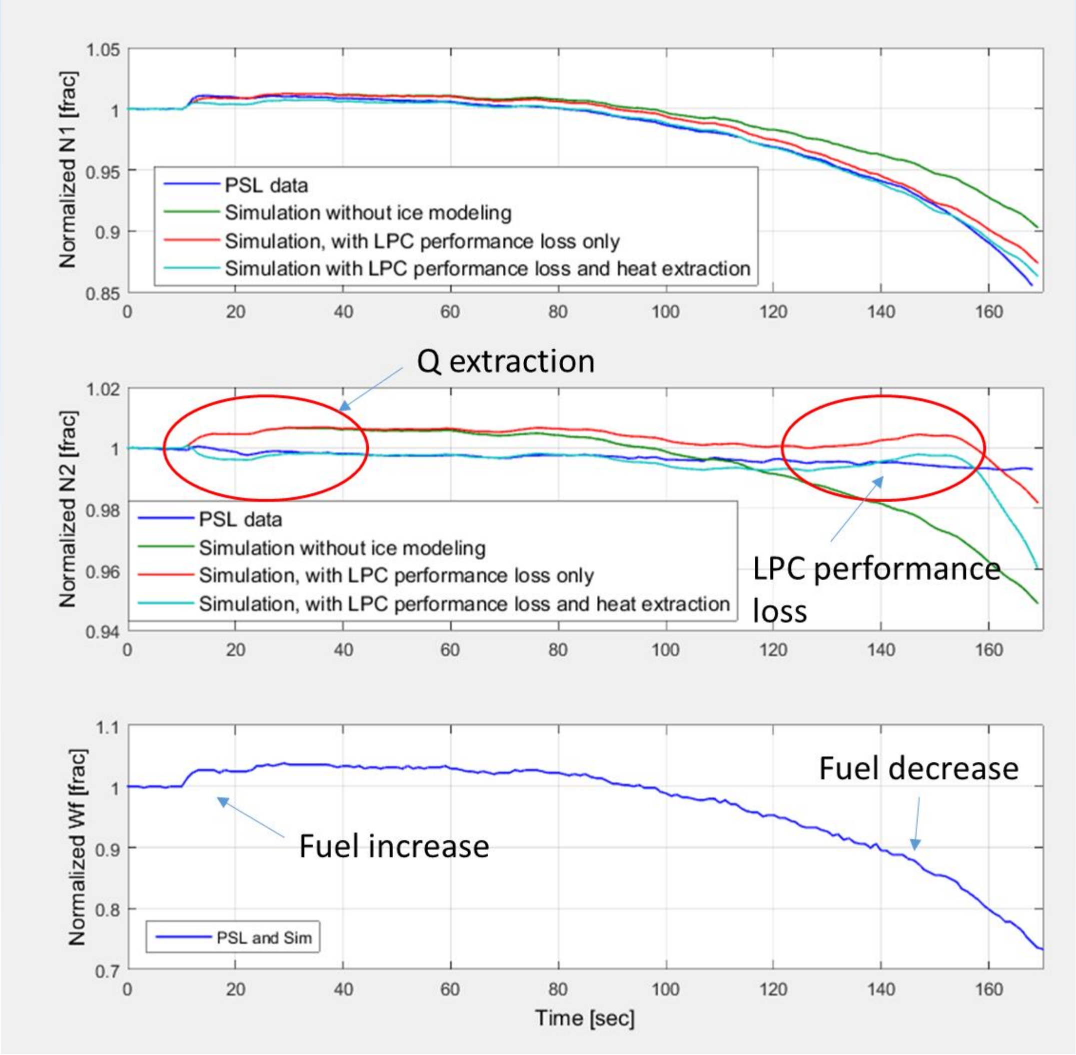
Baseline Steady State Simulation



Simulation of Ice Accretion

Simulation:

- Input/output model without controller
- Fuel flow values from PSL data are fed into the T-MATS model
- Ice cloud injected at 10 sec.
- Heat extraction due to ice particle is simulated to improve the model accuracy



Detection of Engine Ice Accretion

- Typically 5 – 7 control sensors present in an engine
- Icing causes a change in the LPC operational characteristics
  - Decrease in flow rate
  - Generally a decrease in efficiency
  - Decrease in surge line
- Goal: use the available sensors to estimate the change in LPC performance
- Constraint: Must be computationally simple

Detection of Engine Ice Accretion - Approach

- Linear estimator
  - Estimate shift in LPC efficiency and LPC flow capacity
  - Sensor residuals are based on corrected fan shaft speed, corrected core shaft speed, and corrected EGT
- Assumptions:
  - No other component faults
  - This ensures that all changes in engine operation are due to ice accretion
- Previous results:
  - Good and early detection during steady state operation
  - Limited success in detection during transient. And, the detections are usually too late for mitigation.

Mitigation of Engine Icing

- Ideally, completely avoid ice accretion
- If we can detect accretion early can the engine controller act to mitigate the impact of the ice blockage?
- Potential mitigation strategies:
  - Operate actuators off-nominally to change operating point
    - Close inter-compressor bleed valve or move HPC inlet guide vanes off schedule
  - Use existing airframe integration in novel ways
    - Power take-off, Customer air bleed
  - Change shaft speed to cause ice to shed
- All of these approaches require iteration with an icing code to determine the effect of the new condition on ice accretion!

Conclusions

- A T-MATS engine model was created to simulate the engine ice accretion
  - Baseline testing showed good match with steady state data
  - LPC performance maps degradation due to the ice accretion were implemented
  - Thermal extraction due to ice melting was also simulated
  - Dynamic simulation showed very good match during the ice accretion
- Early detection of engine ice accretion is an on-going research
- Possible mitigation strategies discussed

Future Research

Engine Icing Control Element:

Re-start in FY16

- Develop and test a realistic controller that shows the interaction of ice accretion and the rollback phenomena
- Add the high ice water content simulation to the inlet to simulate the inlet condition
- Demonstrate the correlation of high ice water air and engine performance for selected controller designs
- Extend the modeling to include future engine configurations such as N+3
- Develop early detection algorithms for icing conditions that may be susceptible to ice accretion
- Develop mitigation algorithms that can reduce the risk of ice accretion at high ice water content conditions.

References

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- May, R.D., Guo, T-H., Simon, D.L., "An Approach to Detect and Mitigate Ice Particle Accretion in Aircraft Engine Compression Systems," ASME-GT2013-95049, ASME TurboExpo 2013, San Antonio, TX, June 3-7, 2013.